between wythes help the wall to behave in a more monolithic fashion for out-of-plane demands. One form of construction where interior vertical joints are deliberately not filled is cavity-wall construction. Used in many northeastern United States buildings, the cavity helps provide an insulating layer and a means of dissipating moisture. The cavity also reduces the out-of-plane capacity of the wall.

Material properties—such as compressive, tensile, and shear strengths and compressive and shear moduli—vary widely among masonry units, brick, and mortar. An important issue for in-plane capacity is the relative strength of masonry and mortar. Older mortars typically used a lime/sand mix and are usually weaker than the masonry units. With time, cement was added to the mix and mortars became stronger. When mortars are stronger than the masonry, strength may be enhanced, but brittle cracking through the masonry units may be more likely to occur, resulting in lower deformation capacity.

Given the wide range of masonry units, construction, and material properties, developing a comprehensive methodology for the evaluation of earthquake damage is difficult. The methodology in this document is most directly relevant to solid clay masonry laid in running bond with a typical spacing of header courses. Additional issues that should be considered for different conditions are identified in some cases.

For additional general background on URM materials, see ABK (1981a), FEMA 274, and Rutherford and Chekene (1997).

There is significant diversity in the characteristics of the structural systems used in URM bearing wall buildings. A primary issue is the rigidity of floor and roof diaphragms. While the 1994 UCBC includes provisions for both flexible and rigid diaphragms, the original ABK research, upon which it was based, primarily addressed flexible wood diaphragms (ABK, 1984). While such wood-diaphragm buildings are the most common, there are a substantial number of buildings with more rigid diaphragms, particularly in areas outside California. These include concrete slabs spanning between steel beams, hollow concrete planks, and brick and HCT arches spanning between steel beams.

Buildings with rigid floor and roof diaphragms will respond to earthquake shaking in a substantially different manner from those with flexible diaphragms. When rigid diaphragms are used, the traditional model of building behavior used in the building code is that of a lumped-mass system. In this model, the diaphragms represent the mass, and the vertical elements (such as walls) are flexible and are the primary source of the dynamic response experienced by the building. In contrast, in URM buildings with flexible diaphragms, the ABK model assumption is that the ground motion is applied to the ends of the flexible diaphragms without significant amplification. Any amplification that occurs is caused by the dynamic response of the diaphragm and the coupled out-of-plane walls. In some cases, the diaphragm may yield, limiting the forces that can be transmitted to the in-plane walls. In rigid-diaphragm URM buildings, diaphragm yielding is unlikely, and the frequency of response of the wall and diaphragms is likely to be much closer.

The methodology in this document is most directly relevant to URM bearing-wall buildings with flexible diaphragms. While FEMA 273 generally separates diaphragm issues from wall issues, there can be interrelationships between the two. Such issues are pointed out where appropriate.

### 7.1.3 Seismically Rehabilitated URM Buildings

When evaluating earthquake damage to unreinforced masonry buildings, it is important to determine the extent of seismic rehabilitation work that may have been performed, because this can affect the interpretation and significance of the damage. For example, if the building has not been seismically rehabilitated, horizontal cracking near the floor lines may be related to buckling of a slender wall. However, if wall-to-diaphragm ties have been installed in a rehabilitation effort, then the cracking may be related to an out-of-plane bed-joint sliding-shear failure in the mortar below the wall ties. If the wall is backed by shotcrete as is commonly done in a seismic rehabilitation, then the masonry wall cracking may be less significant than if there were no concrete present.

URM buildings have been the focus of seismic-hazard mitigation policies, evaluation and rehabilitation standards, and seismic-strengthening efforts. On the west coast, in California in particular, a substantial number of URM buildings have been rehabilitated. Seismic strengthening practices and standards have evolved over the years, and the scope of work and

expected performance of the rehabilitated buildings varies significantly. It is important to appreciate the variety of potential rehabilitation work that may be encountered in the field. Using FEMA 273 terminology, performance objectives used in URM rehabilitation include:

- Limited Partial Rehabilitation efforts, such as those that address only certain specific elements such as parapets (e.g., San Francisco Parapet Safety Program).
- More substantial Partial Rehabilitation efforts such as the San Francisco "Bolts-plus" provisions that address parapets, wall-diaphragm ties, and wall bracing.
- Reduced risk rehabilitation programs such as the City of Los Angeles Division 88 and RGA requirements (Division 88, 1985 and SEAOSC, 1986), the *Uniform Code for Building Conservation*, and FEMA 178 (BSSC, 1992)—all of which address the complete lateral-load-resisting system, but which require only a single-level check of the life safety performance level instead of the two-level check required by FEMA 273. Retrofit approaches using these methodologies may be capable of meeting the Basic Safety Objective if it can be shown that the building can meet the collapse prevention performance level for the BSE-2 earthquake as defined in FEMA 273.
- Basic Safety Objectives, such as the Field Act strengthening requirements for California elementary and secondary public schools.
- Enhanced Rehabilitation Objectives to limit damage and increase functionality have been implemented for a few select buildings.

While many voluntary and mandatory strengthening programs are in place in the west, and the number of rehabilitated URM buildings continues to grow nationwide, the vast majority of the rehabilitated URM buildings are those in Southern California strengthened to Division 88 (City of Los Angeles, 1985), RGA (SEAOSC, 1986) and similar standards and those in San Francisco that have complied with an earlier parapet safety program, but have not yet completed more stringent current requirements.

In general, this document is intended to be used with unrehabilitated buildings. The guidelines for in-plane and out-of-plane wall behavior assume, for example, that the wall has not been strengthened with other materials such as concrete, adhered fabric, or ferrocement overlays. If the URM wall has been strengthened with shotcrete or cast-in-place concrete, then the evaluating engineer will have to exercise judgment about the significance of the damage using both the provisions of Chapter 5 for reinforced concrete and those of Section 7. Generally, greater attention should be given to the damage in the concrete elements because they are usually the primary or intended lateral-force-resisting element. Fabrics and overlays have been the subject of experimental testing, but very limited rehabilitation has actually been performed using these techniques; as a result, they are not addressed in these provisions.

Even though the focus is on unrehabilitated buildings, the guidelines contain descriptions of damage and commentary on its interpretation for certain selected elements in rehabilitated buildings. Such commentary is based on observations from the 1987 Whittier, 1989 Loma Prieta, and 1994 Northridge, California, earthquakes.

## 7.2 Unreinforced Masonry Component Types and Behavior Modes

### 7.2.1 Non-Wall Components

For the procedures in this document, structural systems are subdivided into elements, which are further subdivided into components that can be related to specific modes of behavior during seismic shaking. Components within URM bearing wall buildings include parapets, appendages, wall-diaphragm ties, diaphragms, and walls. The focus of this document is in-plane wall behavior modes. For other building types, such as concrete wall buildings, earthquake damage is primarily related to the in-plane behavior of the wall or displacement incompatibility between the walls and other elements. For URM bearing wall buildings, however, other elements and components figure prominently in observations of actual damage. In many cases, non-wall component damage may occur before in-plane damage to the wall becomes significant. These other features and their common behavior modes are discussed briefly below. The remainder of the document focuses on wall elements and components.

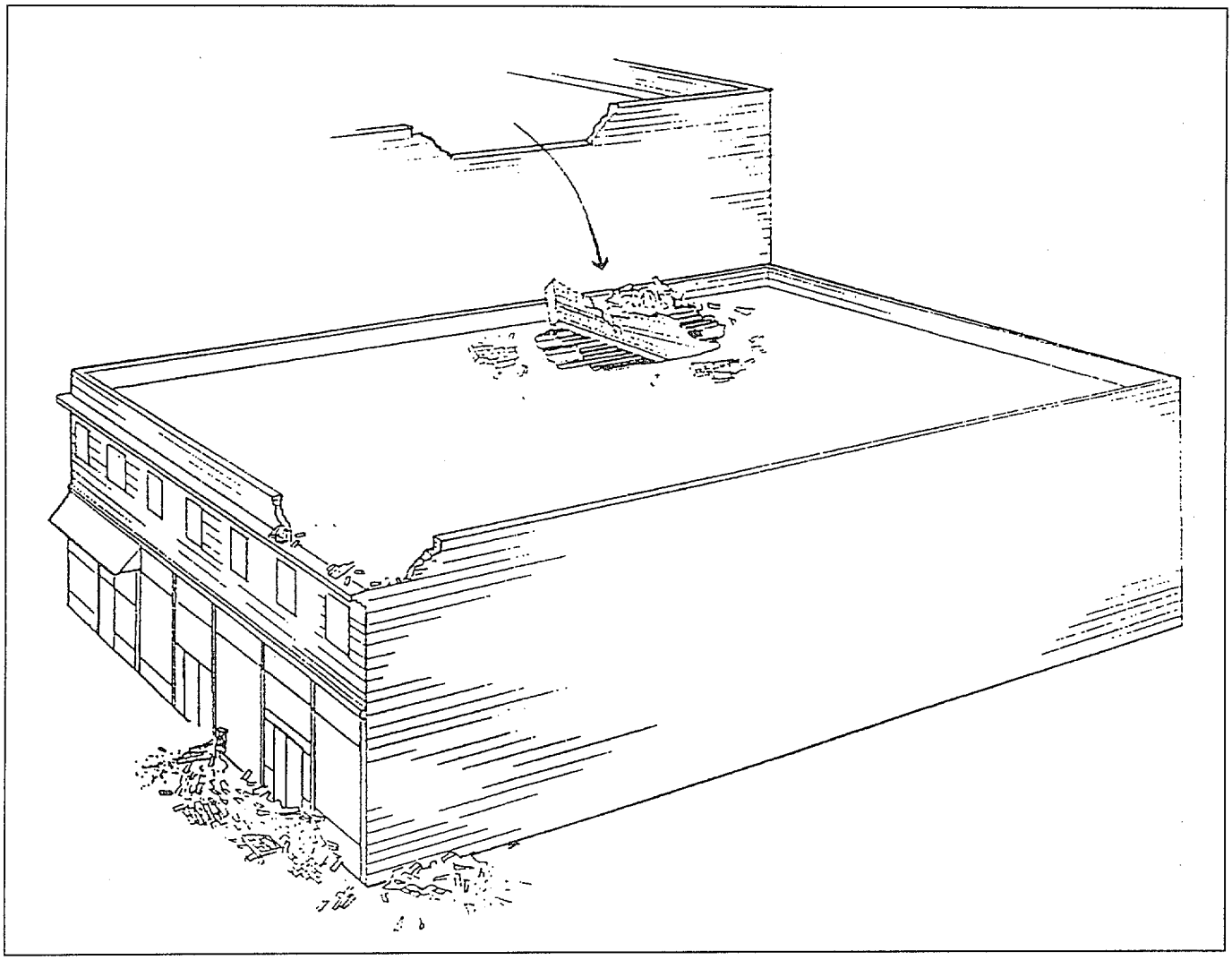

*Figure 7-1* *Diagram of Parapet Failure (from Rutherford and Chekene, 1990)*

*Parapets:* These short extensions of walls above the roof typically occur at the perimeter of the buildings and are primarily present for fire safety or aesthetic reasons. As originally constructed, they are not braced back to the roof and are thus susceptible to brittle flexural out-of-plane failure (see Figures 7-1 and 7-2). Braced parapets typically fail at the connections between the parapet and the brace (see wall-diaphragm tie failures for similar examples).

*Appendages:* This category includes veneer, cornices, friezes, pediments, dentils, brackets, statuary, and finials—in short, any minor masonry feature that is susceptible to falling. Damage may result from excessive accelerations of appendages and deformations that cause connection failures between the appendage and the structure; delamination of veneer can result from missing or inadequate ties; deformation incompatibility between the appendage and structure can cause cracking and spalling; and pounding against adjacent buildings can lead to localized falling hazards (see Figures 7-3 and 7-4).

*Wall-Diaphragm Ties*: In the United States, wall-to-diaphragm ties in existing URM buildings are generally limited to low-strength tension connections called "government anchors" or "dog anchors," in which one end of a steel bar is embedded one wythe in from the outer face of the wall and the other end is hammered into the side of a wood joist. These ties typically occur where joists bear on the walls, not where they are parallel to the walls. Wall-diaphragm separation due to inadequate or missing tension ties can lead to out-of-plane failures of walls; missing shear ties can lead to the

*Figure 7-2* *Photo of Parapet Failure (from Rutherford and Chekene, 1990).*

diaphragm sliding along the in-plane walls and then pushing against the walls perpendicular to the movement, resulting in corner damage to the walls (see Figures 7-5, 7-6 and 7-7). In rehabilitated buildings, a variety of tie failures have been observed, including bond failures between the masonry and the cementitious grout used in older drilled dowel connections, cone failures due to shallow embedment and/or weak masonry, pullthrough of through-plated anchors, and bed-joint sliding near ties. Wall-diaphragm failures are often associated with thin walls (such as two-wythe walls at upper stories), poor mortar conditions, and lack of sufficient overburden pressure.

*Floor and Roof Diaphragms*: Three categories of diaphragms can be identified: rigid concrete slab diaphragms, flexible wood and metal diaphragms, and intermediate systems such as hollow concrete planks and brick and HCT arches spanning between steel beams. In flexible diaphragms, excessive deflections can lead to out-of-plane wall damage. Hollow concrete plank systems may lack adequate interconnections to function as a continuous load path. Brick and HCT arch systems may be susceptible to vertical failure if beams separate locally. See Figure 7-8 for diagrams of some of the diaphragm types. Rigid concrete diaphragms are generally not significantly damaged or the source of damage to other elements in URM bearing wall buildings, but they do affect the dynamic behavior of the building.

Table 7-1 summarizes behavior modes for non-wall URM elements, providing the source of the deficiency, type of damage, and intensity of ground shaking usually required to produce the damage. The intensity of ground shaking is a qualitative judgment based on actual earthquake reconnaissance and damage collection efforts. Individual buildings may respond in a different manner. Even though some types of damage do not generally lead to collapse, they can nonetheless endanger life safety either within the building or around the perimeter due to localized falling hazards. A simple example is an exterior parapet failure, which rarely leads to building collapse, but still poses a risk to pedestrians adjacent to the wall. Damage to non-URM wall elements is typically brittle or force-controlled, and it often does not affect the overall force-displacement relationship for the building. The component guides in this volume focus on wall damage. For non-URM wall elements that can affect the overall force-displacement relationship, such as wall-